REDUCING SYSTEMATIC ERRORS FOR SEISMIC EVENT LOCATIONS IN ANISOTROPIC REGIONAL STRUCTURES

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ABSTRACT

In CTBT applications many events of interest are only detected at regional distances. Providing more accurate prediction of P-wave propagation at regional distances is therefore of particular importance in seismic event location. At such distances (2 -14) the phase Pn is the seismic phase that is most frequently reported and which thus controls the location accuracy. We are working on reducing systematic errors in Pn travel-times and thus seismic event location at regional distances.

In recent work the P.I. has mapped lateral and anisotropic variations in Pn velocities beneath continents across the globe (Smith and Ekstrom, 1999). This work provides the most comprehensive and possibly most accurate mapping of anisotropic Pn velocities available to date. While the lateral variations in Pn velocities that were mapped were strong, and are likely to contribute to improved location capabilities, strong (up to 10%) anisotropic signatures were also observed. The horizontally travelling Pn phase should therefore accumulate large travel time residuals due to both heterogeneity and anisotropy, which would result in large systematic location errors. The question remains whether this new mapping can provide, in a practical sense, significant reductions in systematic event mislocation at the regional scale. Preliminary results indicate that, even in areas of good station coverage, a distinct difference in location is obtained using anisotropic models.

OBJECTIVE

In CTBT applications many events of interest are only detected at regional distances. Our objective is identification and reduction of systematic errors in the location of events determined using regional seismic data. At such distances (2 -14) the phase Pn is the seismic phase that is most commonly reported and which thus controls the location accuracy. In order to accurately locate seismic events, whether natural or artificial, by traditional travel-time methods one must first be able to accurately predict arrival times. Historically travel-times have been calculated using one-dimensional seismic velocity models (e.g. Jeffreys and Bullen, 1940; Herrin et al., 1968; Herrin and Taggart, 1968; Herrin, 1968; Dziewonski and Anderson, 1981; Kennett and Engdahl, 1991). However, the Earth is composed of rocks which vary laterally at varying length scales (e.g. Crosson, 1976; Engdahl et al., 1977, 1982; Engdahl and Billington, 1986; Dziewonski, 1984; Su and Dziewonski, 1993) and can be anisotropic (e.g. Christensen, 1966; Kumazawa and Anderson, 1969; Hess, 1964; Raitt et al., 1969; Forsyth, 1975; Tanimoto and Anderson, 1984), resulting in travel-times which do not match those predicted by these one-dimensional velocity profiles. In addition, at regional length scales global Earth models, which are largely based on long-period surface waves and vertically arriving body waves, provide poor first arrival travel-time predictions. Providing more accurate prediction of P-wave propagation at regional distances is therefore of particular importance in event location. When attempting to satisfy the location requirements of the CTBT it is essential to obtain the most accurate location possible, with the minimum necessary computing time

The question remains as to whether the current generation of regional models can usefully contribute to relocation problems. While it has already been well established that variations in regional phases such as Pn can lead to large mislocations of the epicenter (Herrin and Taggart, 1962), progress has been slow in routinely applying regional models to locations for global catalogs. This is probably because most of the Pn velocity models produced are of a highly local nature (e.g. Hess, 1964; Raitt et al., 1969; Bamford, 1977; Fuchs, 1977; Hirn, 1977; Vetter and Minster, 1981), and no systematic global mapping of Pn velocities has been attempted. In addition although azimuthal anisotropy is a known feature of Pn

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propagation (e.g. Beghoul and Barazangi, 1990; Hearn, 1996), most previous studies of Pn anisotropy have not mapped lateral variations in azimuthal anisotropy, but instead produced, if anything, a single estimate for an entire region.

In recent work the P.I. has mapped lateral and anisotropic variations in Pn velocities beneath continents across the globe (Smith and Ekstrom, 1999). This work represents the most comprehensive and possibly the most accurate mapping of anisotropic Pn velocities available to date. This provides the first opportunity to truly test the possibility of applying an anisotropic Pn velocity model to calculation of travel-times to improve regional locations for events distributed in different parts of the world. The question remains whether this new mapping can provide, in a practical application, significant reductions in systematic event location at the regional scale. Our work is aimed at applying this new mapping of Pn anisotropic structure to investigate the possible systematic errors produced by lateral heterogeneity and azimuthal anisotropy

RESEARCH ACCOMPLISHED

As a preliminary investigation we have already implemented a grid search relocation algorithm and applied this to the Pn mapping of Smith and Ekstrom (1999) to test for systematic errors in location. In this study we have taken several events in western Europe as we have good mapping of both Pn velocities and anisotropy in this area. Figure 1 shows the lateral variations in Pn velocities of Western Europe extracted from our dataset. Figure 2 shows the fast azimuths of the Pn anisotropy from our model.

In this preliminary relocation experiment we use travel-time data from the ISC database. The ISC location is used as a first estimate. The fit of travel times is then calculated for this location and for a set of points on a rectangular grid at 10-km spacing. The minimum in the rms of the travel times is then selected as the new location estimate and the travel-time misfits recalculated using a smaller grid spacing. This is repeated until the travel-time misfit appears to converge. This procedure has been performed for a selection of earthquake events for isotropic, laterally heterogeneous, and anisotropic structures. In this preliminary test for systematic effects great-circle raypaths were used. The results of this can be seen in Figure 3.

Figure 3(a) shows the relocation vector of the events using laterally varying Pn velocities. The base of the arrow lies at the location found with an isotropic model. The arrow points in the direction of the location found by use of the laterally varying Pn velocities. The arrow length is proportional to the distance between the two locations, and a 10 km displacement is shown for scale. Similarly, Figure 3(b) compares the relocation vector of the events when using azimuthally anisotropic Pn velocities. Again the base of each arrow lies at the location found with an isotropic model.

With these events “ground truth” is not known and so comparison to a “true” location is not possible. However, what is demonstrated is a noticeable systematic difference between the locations found with the different models. In both cases the revised locations have moved away from stations where the model predicts a fast traveltime anomaly, and towards stations where the traveltime anomaly would be slow. If we assume that the anisotropic locations are the most accurate, being based on the most detailed model, this would suggest that failure to account for anisotropic structure introduces significant systematic errors.

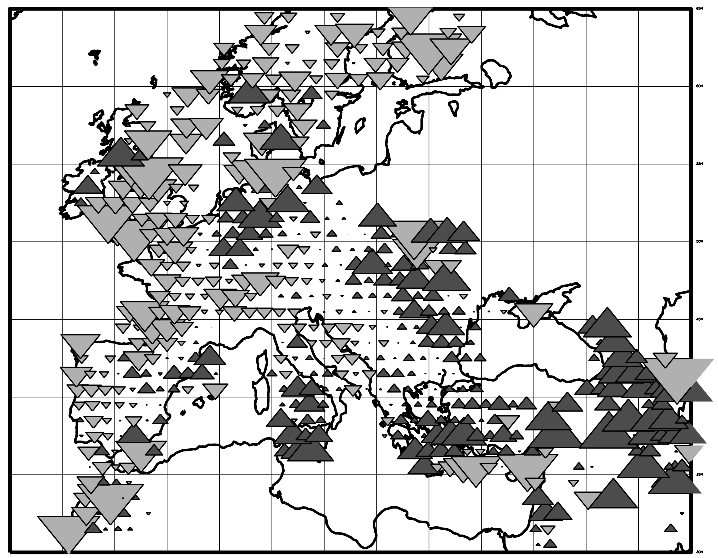

Figure 1: Lateral variations in the isotropic Pn velocity across Western Europe. Upward pointing triangles are slow, downward pointing triangles are fast. The size of the triangle is proportional to the anomaly. Values are in the range 7.8 to 8.4 km/s.

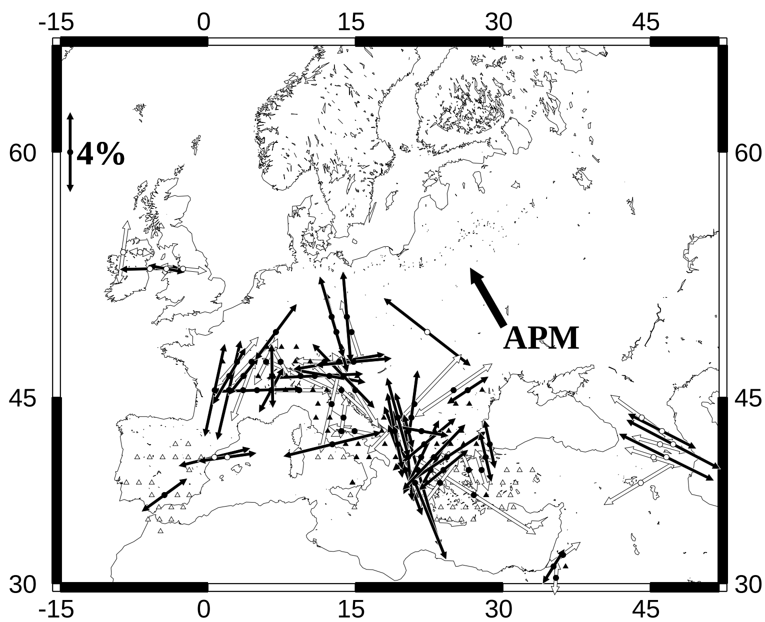

Figure 2: Pn anisotropy results for Western Europe. The center of each symmetric arrow pair is plotted at the center of the cap. Arrows point in the direction of fast Pn propagation and are proportional to the strength of anisotropy. Black arrows are higher quality estimates. Black and white center points indicate 1.5° and 3° radius caps respectively. Triangles show the location of null results. The absolute plate motion vector is also shown (Minster and Jordan, 1978).

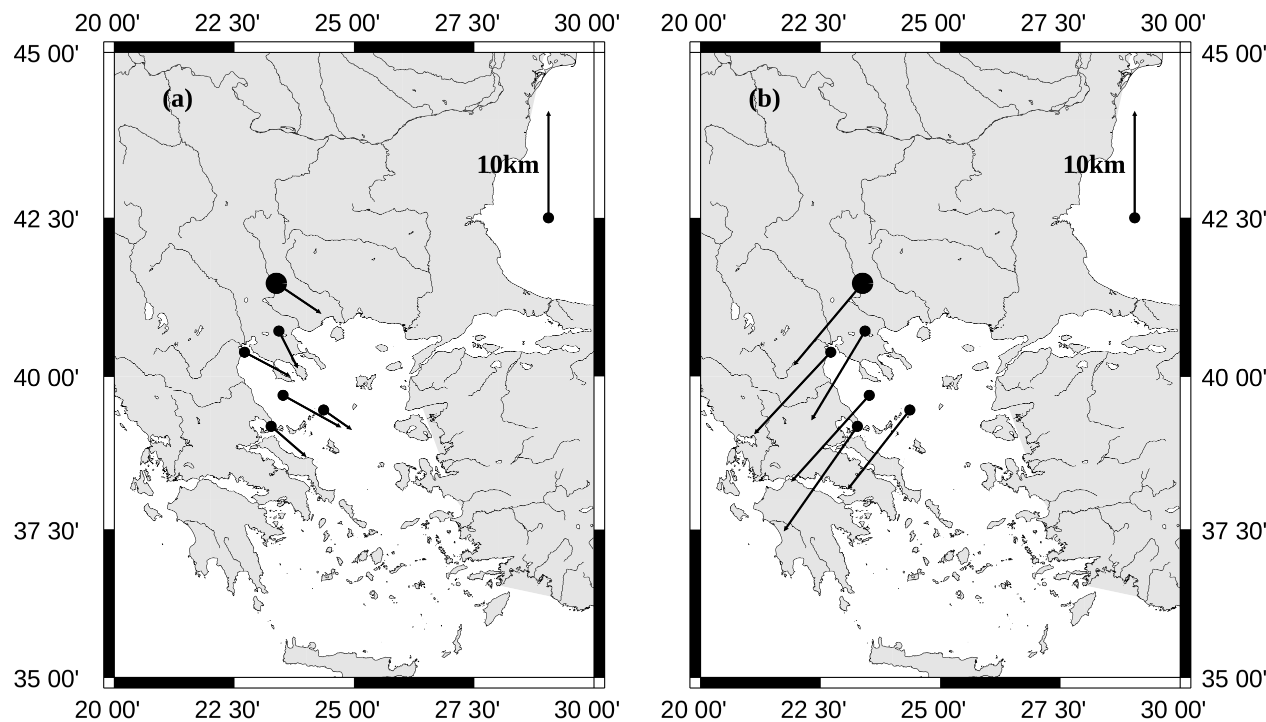

Figure 3: (a) Relocation vectors of the events using laterally varying Pn velocities. The base of the arrow lies at the location found with an isotropic model. The arrow points in the direction of the location found by use of the laterally varying Pn velocities. The arrow length is proportional to the distance between the two locations, and a 10 km displacement is shown for scale. (b) Relocation vectors of the events when using azimuthally anisotropic Pn velocities. Again the base of each arrow lies at the location found with an isotropic model.

Comparing Figures 3(a) and (b) a distinct difference in relocation azimuth is also observed, suggesting that when only lateral heterogenity in Pn velocities is considered significant systematic errors may still be introduced. The change in location for these events is larger when including anisotropy (Figure 3(b)) in this case averaging approximately 10 km.

This example is expected to be an example of minimum effect as the station coverage for this region is good. In areas with much poorer azimuthal coverage the location may be entirely controlled by the anisotropy. This may be seen by considering the strength of anisotropy observed. The average Pn anisotropy observed is about 6%. If we take an isotropic (average) Pn velocity of say 7.9 km/s then 6% anisotropy corresponds to a maximum anisotropic velocity of 8.4 km/s. If we use Pn observations over 2 -11 and apply the isotropic velocity value we can achieve maximum travel-time misfits (assuming propagation along either the fast or slow directions) of 1.6 to 8.8 s, corresponding to mislocations of 12.7 to 69.7 km. Obviously in most real situations it is unlikely that the only propagation will be along the fast or slow axis but this gives some indication of the effect anisotropic structure could have in areas where azimuthal coverage is poor. Proper application of an anisotropic Pn velocity model should remove such errors.

CONCLUSIONS AND RECOMMENDATIONS

In order to establish whether relocation using our anisotropic Pn velocity model does infact translate into a reduction in relocation errors we must have some benchmark by which to test our relocations. One way of establishing whether errors have been reduced is to perform relocations of events where the hypocentral parameters of the event are already known, and have not been derived from seismological data. Ideal examples of this type of event are explosion events, such as peaceful nuclear explosions (PNEs). The first step in our future work will be to establish a list of events for which we have independent estimates of the hypocentral parameters. Our preliminary dataset for this will be the list already published by the author in earlier work (Smith and Ekstrom, 1996, table 1) which includes 26 explosions in various geographic locations. We are however working at expanding this list. For example, at present we are recovering all of the travel-times from the Gnome experiment (Carder, 1962). This was a PNE that was detonated in New Mexico in 1962, prior to the establishment of the modern ISC database. This large event was recorded by an unprecedented number of stations across the U.S. and should provide useful test data for our study. In future we hope to be able to incorporate more recent “ground truth” events, catalogs of which are currently being compiled by several researchers in response to the CTBT challenge. For these more recent events we will use the actual arrival time data published on the web by the IDC, thus testing in a manner as close to actual IDC operations as possible the capability of our methods as applied to the IMS monitoring network stations.

The second stage in future work will be to develop and test a method of applying the anisotropic Pn velocity model to calculation of arrival times and event locations. Clearly the lateral heterogeneity and azimuthal anisotropy in our model could produce deviations from a great-circle ray-path from event to station which may be equally as important as the anomalies themselves in influencing travel-times. However, calculation of such ray-path anomalies is likely to be a computational involved process and therefore not necessarily one that would be practicable for monitoring efforts. Part of this project will therefore involve investigation of the importance of such raypath anomalies.

To achieve this we will perform and compare relocations using a variety of models and approximations. These will include isotropic Pn velocity models, Pn models incorporating lateral heterogeneity but no anisotropy, and also our full anisotropic Pn velocity model. Relocations will be performed using both great-circle raypaths as well as raypaths calculated using the anisotropic model. In this way we will be able to quantify the various levels of improvement possible to help determine if the reduction in the error ellipse provided by accurately accounting for raypath deviations is worthwhile given the additional computational requirements.

Our preliminary work will examine the relocation of test events within North America as the locations of PNEs in this region are well known, and the Pn velocity and anisotropy is well sampled. However, at all stages testing will be undertaken with the practical operating procedures and challenges of the IDC in mind.

For this reason we will make maximum use of phase data from stations contributing to the IMS, apply our methods to as diverse a range of geographic locations and situations as possible, and statistically quantify the degree of improvement for the additional cost in computational time. In this manner we hope to maximize the practical usefulness of the product of our research for monitoring purposes.

Key Words: Pn, anisotropy, regional phases, CTBT, relocation.

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